The Plethora of Science Afforded by a Lunar Swirl

A White Paper to the Planetary Science Decadal Survey Committee

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Topic

Lunar swirls are one of the most beautiful and enigmatic features in the Solar System.

Lunar swirls are unusual features found in discrete locations across the Moon's surface. They are characterized by having a high albedo, appearing optically immature (i.e. having the optical characteristics of a relatively young regolith), and (often) having a sinuous shape. They impart no topography, but rather overlay the existing topography [1]. Swirls occur on lunar maria and highlands - they are not associated with a specific lithologic composition or typical planetary surface process (e.g., volcanic, tectonic, or impact cratering). Swirls on the maria (the type example being Reiner Gamma) are accentuated by low albedo regions (dark lanes) that wind between the bright swirls, and sinuous (swirly) morphology, whereas those on highland terrain appear less prominent and exhibit simpler shapes, such as single loops or diffuse bright spots. Every swirl is coincident with a local region of strong remanent magnetism [2] on a planetary body that does not currently generate its own magnetic field. Although, not every magnetic anomaly has an associated lunar swirl (Fig. 1). The reason for this is still unknown. Lastly, lunar swirls appear to be unique to the Moon [3, 4].

The two prevailing hypotheses for lunar swirls are that they were created by comet impacts [5] or that the magnetic fields shield the surface from weathering by solar wind protons [2]. Evidence from multiple studies using a variety of instruments and methods converge on the latter hypothesis [e.g., 1, 6-14].

Lunar swirls should be the top priority target of the next lunar mission. The swirls are not only a fascinating feature of the Moon, they are a laboratory to study the solar wind, space weathering, plasma weathering, and plasma kinetics. A robotic or human mission to a swirl will help answer questions of interest to planetary science [15] as well as the broader scientific community. Within this white paper we present examples of broad scientific interest in lunar swirls as well as some example mission types.

There are several locations where swirls occur. So while the swirls are themselves scientifically interesting, there are specific swirl locations that would simultaneously satisfy the objectives of other lunar missions. Examples of such swirl locations are presented in the Recommendations section.

Significance

Lunar swirls are of interest to planetary science as well as the broader scientific community.

Remanent Magnetic Fields: Every swirl is associated with a magnetic anomaly. In addition, it has been shown that the optically brightest part of a swirl or group of swirls correlates with the location of peak magnetic field intensity [16]. Models of the distributions of the magnetic source material, when constrained by the observed albedo patterns produce magnetic field vectors consistent with magnetometer measurements [9]. Specifically, these models show that strongly horizontal surface fields can generate the bright swirls, while vertical surface fields can generate dark lanes [13, 17]. Based on these models, the more intricate swirl morphologies can be used to infer small-scale structure in the near-surface magnetic field as well as the depth and orientation of the magnetic source material.

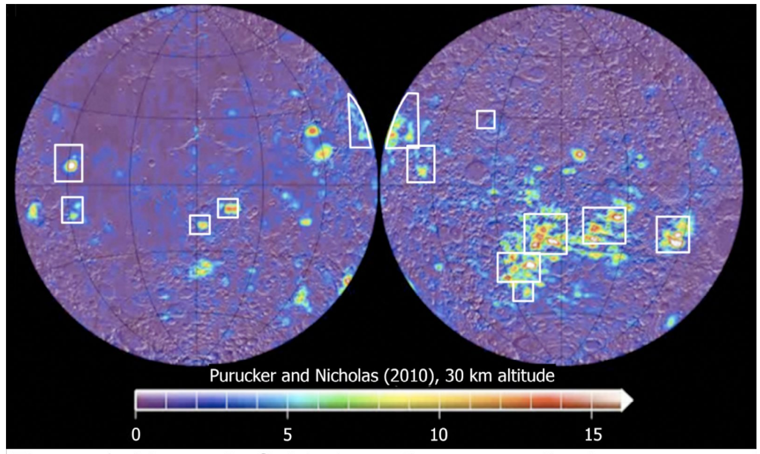

Figure 1: Magnetic field strengths across the lunar surface.White boxes are locations of identified swirls.

Planetary Photometry: Previous studies labeled swirls "photometric anomalies" based on observations that their surfaces are forward scattering at virtually all phase angles [5, 18, 19, 20]. This could explain their optically immature appearance, except that swirls are still highly reflective at large phase angles, whereas fresh crater ejecta is not. This photometric departure was interpreted as indicating that swirl surfaces have a unique texture - distinct from typical immature and mature surfaces [19, 20]. This observation formed the basis for the hypothesis that lunar swirls are relatively recent comet impacts. Proponents of the comet impact hypothesis argue that such an event would scour the surface, removing the finest particles in the turbulence of a comet impact [5, 18, 21] thus explaining the unique photometry of swirls.

Until recently [22], this has been the "thorn in the side" of the solar wind stand-off model for swirl formation because this hypothesis cannot explain why the swirls would have a photometrically unique surface. A comprehensive study [22] using photometric observations from the Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) and radiative transfer modeling found no photometric difference between on-swirl compared with non-swirl regolith. This analysis found that fresh highland impact crater ejecta to be among the most backscattering of all lunar materials. *In situ* observations of textural and compositional regolith properties would be instrumental in improving our understanding of impact processes on different planetary bodies as well as improving photometric techniques used to create seamless global maps from swaths of orbital data.

Planetary Volcanism: The source of the magnetic anomalies remains a question, but one hypothesis associates them with lava tubes, dikes, and/or sills in the shallow crust. Utilizing the shape of the swirls and estimates of the surface magnetic field strengths [23] concluded that the underlying magnetized rocks must be shallow and narrow, such as a sill or lava tube. This conclusion is supported by the identification of elongated magnetic anomalies in a surface vector map generated by combining Lunar Prospector and Kaguya magnetic field measurements [9].

Space Weathering: The optical properties of the swirl surfaces (on-swirl) compared with regions adjacent or between swirls (off-swirl), and locations not associated with magnetic anomalies (non-swirl), demonstrate the different ways the Moon's surface material is altered by solar wind ions versus micrometeorite impacts [24]. This is because the magnetic fields have no influence on the trajectory of micrometeorites, but can influence low-mass solar wind ions (protons and electrons). Spectral data demonstrate that space weathering effects on-swirl are retarded [1, 7, 8, 10, 11], and that off-swirl surfaces mature much faster than on-swirl surfaces and even non-swirl surfaces [7, 8]. Since the swirls are weathered almost exclusively by micrometeorites, in situ analysis and returned samples can be used to study their isolated effect on the maturation process [24]. This would also benefit asteroid studies. Retardation of the weathering process on-swirl indicates that the solar wind is the dominant form of weathering at the Earth-Moon distance. However, at the Asteroid Belt it may be micrometeorites that dominate. Spectroscopic differences between asteroid and lunar surfaces due to composition and proximity to the Sun have kept this controversial [25].

Sampling Fresh Material: Since space weathering is retarded on-swirl, while normal (and possibly accelerated) space weathering rates are occurring off-swirl, a lander or rover of limited mobility could sample materials of the same absolute age, but different apparent age (optical maturity) and vice versa. In a small area one can sample material formed at the same time (e.g., by volcanism, by impact), and/or exposed by impact gardening at the same time, while also sampling fresh material and its weathered counterpart [26].

Lunar Water: Several observations from both Earth-based and orbital platforms [27, 28, 29, 30] have confirmed the presence of surficial and sometimes transient water (OH/H_2O) on the lunar surface. These observations raise several questions: How does this surficial water form? What form is the water (liquid, solid)? How and where does the water reside on the surface? What factors control its occurrence and stability: latitude, regolith composition, maturity?

Moon Mineralogy Mapper data show that the optically bright swirls are depleted in OH/H_2O relative to their surroundings [8], an observation that supports the solar wind deflection model for the swirls, as the magnetic anomalies are strong enough to interact with charged, low-mass solar wind particles (protons and electrons). Thus, the creation of OH and H_2O is spatially controlled by the magnetic anomalies, making swirls ideal natural laboratories to study the surface hydration phenomenon [31].

Plasma Physics, Mini-magnetospheres & Electrostatic Fields: When solar wind plasma impinges on a horizontal magnetic field, due to inertia and an opposite charge sign, ions and electrons interact differently. This results in electrostatic gradients and local ambipolar electric fields [36]. Particle measurements by orbital spacecraft have shown that electrons can be temporarily trapped in the closed field lines of a magnetic anomaly [37]. A density halo/mini-magnetosphere forms. If a lunar magnetic anomaly has a favourable structure, up to 10-50% of incident solar wind protons may be reflected [38, 39]. As a result, the underlying lunar surface will be partially shielded from the solar wind flux [6, 33, 40]. It makes lunar swirls an ideal place to observe charged particle interactions with a magnetic field involving complex geometries [14, 32].

When the flow of solar wind is obstructed, such as by a crater rim, electrons build up in the plasma wake (shadowed side, or “lee” of the solar wind). The plasma wake electrostatically diverts ions, generating a surface potential that can reach kilovolts [41, 42].

Given the spatial extent of the associated magnetic anomalies with respect to the local plasma gyro- and inertial scales, swirls regions will also provide a deeper insight into the solar wind interaction with the near-surface lunar plasma environment and its electromagnetic properties.

Electrostatic Dust Transport: Electrostatic dust charging and transport is a long-standing problem, which may have important implications in shaping lunar surface properties [34]. The generated electric field, described above, could electrostatically manipulate lofted dust. Electrostatic dust transport may contribute to the formation of the swirls by causing the finest dust particles to preferentially accumulate [35]. Investigations of this process *in situ* would help answer remaining questions about the swirl formation. Moreover, the magnetic anomalies may be useful for partial protection from dust, and in the very least investigating this process at a swirl could help improve methods of dust control on the Moon.

Energy resource or energy shield: It is possible that the electrostatic field generated by the interaction between solar plasma and the magnetic anomaly can be controlled by the geometry of the magnetic anomalies in useful ways; either through protection and/or as an energy resource. The effectiveness of a magnetic anomaly as a shield can potentially be increased by introducing additional plasma, such as xenon gas, which can be easily ionised by UV-radiation from the Sun [32]. The kind of passive shielding that a lunar magnetic anomaly may provide will never replace an active deflector shield system, however, it could be useful for extending the longevity of hardware, preventing secondary activation of the ships hull and systems, and deflecting GeV particles [33].

The strength of such an electric field is not dependent on the overall size of the magnetic anomaly, but is related to the local gradient in the magnetic field strength. Locations where the gradient is steep, identified by a sharp bright swirl/dark lane interface, may be a small, but still viable voltage potential to exploit for surface operations.

Heliophysics: Measurements of solar wind ions incident on the lunar surface is of interest to the heliophysics community. Instruments placed at lunar swirls can also observe the behavior of both light and heavy ions interacting with a mini-magnetosphere. Also of interest is how the interaction between the solar plasma and mini-magnetosphere vary with changes in phase angle (from latitude and time of (lunar) day) and energetic solar emissions. Such measurements would provide an opportunity to observe controls on particle mass with varying solar flux [e.g., 12, 13].

If the magnetic anomalies formed at an early age and have been protecting the surfaces from the solar wind ever since, the swirls may contain a record of ancient (pre-4 Ga) solar wind.

Solar System Evolution: Although lunar swirls are very likely as old as the adjacent regolith, swirl surfaces are being protected from at least some of the solar wind protons and the chemical and physical changes they cause. Therefore, swirl surfaces could provide a better preserved record of the late heavy bombardment (LHB) than mature regolith. Material protected from solar wind weathering could provide higher precision radiometric dating of the LHB, the formation of magnetic anomalies, and the ancient activity of the Moon's magnetic core.

Recommendations

Visiting a lunar swirl should be a top priority location for the next lunar mission.

Lunar swirl science can be accomplished on virtually any type of platform from stationary lander to rover, and we refer the Committee to the white paper led by Blewett [15], particularly Section 5, for descriptions of some of the science that can be accomplished by these types of missions. Here we describe additional measurements and mission types not covered in [15].

Deploy an array of low-cost cubesat-type probes equipped with magnetometers to measure the magnetic field and relay the data at a high cycle rate as they free-fall to the surface. If feasible, the probes would be enhanced with the addition of a camera and electron and proton detectors.

A fly-over low altitude orbiter equipped with a hyperspectral imager, ion spectrometers for measuring protons incident and reflected from the Moon, an energetic neutral atom imager, and a mini-magnetometer to measure the magnetic vector along track. This orbiter can even be a cubesat [43]. This could be enhanced by deployment of “ChipSats” which are about the size of a credit card, yet carry a solar array, magnetometer, optical bar camera, and radio. The chipsats measure total magnetic field (just intensity, not vector as they are not oriented). Thus, one could get a detailed hyperspectral image of a lunar swirl region together with vertical information on the magnetic field down to the surface.

A sample-return mission to a swirl can provide a wealth of information, as explained in the previous section. Of course a rover - even a small, short-range rover - is the ideal platform for providing the greatest scientific return. However, a stationary lander that can accomplish a landing precise enough to straddle a swirl with a sharp boundary is also practical. Either of these mission types can sample optically mature and immature material of the same composition and provenance. Being less mature, the on-swirl samples will provide compositional information that is less damaged by weathering effects, so more representative of the composition of the fresh provenance. Comparing both on- and off-swirl materials will provide crucial information about the two major types of space weathering (solar wind and micrometeorites), such as the specific physical and chemical effects each weathering agent has on terrestrial material. Such knowledge not only benefits lunar science, it will help improve models used to determine the compositions of asteroids and outer Solar System moons.

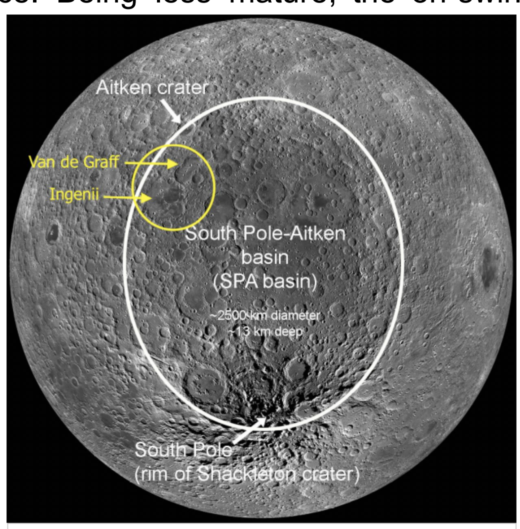

Figure 2: Farside of Moon showing locations of Ingenii and Van de Graff with SPA basin.

Any surface mission to a swirl must be able to measure the magnetic field. Secondary to that is measurements of the proton flux or neutral hydrogen can provide essential information about how the surface hydration phenomenon operates on the Moon and other airless bodies, and quantify the effect and efficiency of the magnetic field on surface hydration.

Other lunar missions objectives that can be achieved at a swirl

South Pole-Aitken (SPA) Sample Return [44]: Ingenii and Van de Graff are locations of prominent swirls and one of the highest magnetic field intensities. Both locations lie in the northwestern portion of SPA (Fig. 2). These locations are ideal for a sample return mission aimed at collecting material representative of the SPA melt sheet as well as the deepest material excavated by the SPA impact.

Lunar Geophysical Network [45]: Lunar swirls are found all over the Moon (Fig. 1). Their distribution allows for a global network of seismic stations to be deployed across the lunar surface while other instruments can be carried to do swirl science.

Planetary Volcanism [46]: There is really no better place than the Reiner Gamma (RG) swirl to study flood volcanism. RG is located right in the middle of vast medium- to high-titanium basalts in Oceanus Procellarum. The northern portion of the RG swirl enters the Marius Hills (Fig. 3), a region riddled with silicic volcanic domes [47].

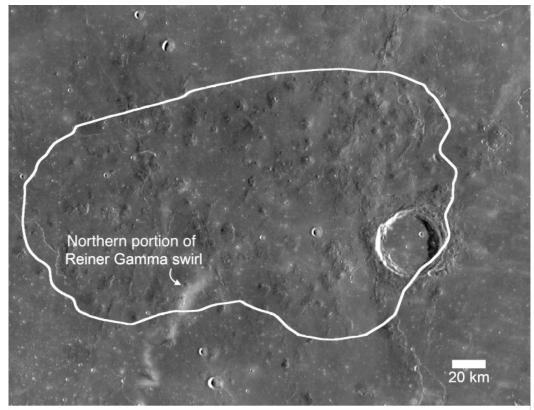

Figure 3: Part of Reiner Gamma is within the Marius Hills region (circled in white).

A Final Word on Diversity in Planetary Science

By their very nature, the lunar swirls are an excellent demonstration of the importance of drawing on perspectives spanning the gamut of planetary science, geoscience, heliophysics, astronomy, technology, engineering, and beyond. Scientific and technological progress prosper from team members with diverse expertise, experiences, and ways of thinking, which are influenced by education, culture, society, and family, as well as their sex, race, gender, economic situation, and more than can possibly be listed here. We ask that the Decadal Survey include recommendations supporting the critical role of team dynamics, equality, diversity, inclusion, and accessibility in planetary science.

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